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NEW FOUNDATIONS FOR
TANK VULNERABILITY ANALYSIS
(WITH 1991 APPENDIX)

MICHAEL W. STARKS

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BALLISTIC RESEARCH LABORATORY
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In this report, the need for new foundations is the subject under consideration. The traditional Ballistic Research Laboratory approach to tank vulnerability analysis is described, problems with that approach are discussed, and the case is made that a probabilistic vulnerability metric is required. It is also shown that appeal to so-called Standard Damage Assessment Lists during the vulnerability assessment process is neither necessary nor desirable.

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1. INTRODUCTION

This is the critical portion of a much longer paper that has been circulated at the U.S. Army Ballistic Research Laboratory (BRL), Aberdeen Proving Ground, MD, concerning foundational questions in tank vulnerability analysis. Nothing grandiose is intended by the focus on foundations; it is a matter of describing the process of vulnerability analysis in a way that is conceptually, mathematically, and physically clear while at the same time doing justice to the complexity of the problems faced daily by vulnerability analysts. As will become evident in what follows, such elucidation is not easy.

When I have discussed issues such as the precise definition of vulnerability measures of effectiveness with others, some have responded, "Who cares?" I think there are both theoretical and practical reasons to care. From a theoretical standpoint, we require an explicit mathematical account of what we are doing when we do vulnerability analysis. In particular, we need to know whether each of our intermediate and final outputs is a percent of a certain kind of capability, a probability that a certain kind of capability will or will not be present, or some altogether different metric. Fundamental scientific clarity requires this. From a practical standpoint, the Army depends on BRL-VLD (Vulnerability/Lethality Division) for lethality estimates. This requires that the wider Army have a correct understanding of the estimates so that they can be correctly used in studies and assessments. The vulnerability community cannot inculcate such understanding in the community if we do not have it ourselves. So there is good reason to care about questions of combat utility, probability of kill, damage criteria, fractional capability, and damage states even though they may seem arcane.

Tank vulnerability analysis clearly requires mappings between physical damage and the loss of tactically significant capabilities. One way of developing such mappings is to assemble a panel of tank experts, describe specific physical damage to them, and ask for an evaluation of the tank's capability given each of the damage states. The result of this process is a so-called Damage Assessment List; selected damage states are listed in the left column, numerical estimates of capability in the right. In 1986–87, considerable resources were expended in developing a new Standard Damage Assessment List (SDAL) for tanks. In an important paper on this recent work, Gerry Zeller and Bradshaw Armendt (1987) develop an argument concerning the "underlying philosophy" of the SDAL which amounts to an account of the foundations of tank vulnerability analysis as it has been historically practiced at the BRL. Zeller and Armendt should be commended for publishing views

which have mostly been communicated by oral tradition in the past. However, I believe that the views enunciated by Zeller and Armendt are seriously deficient; it is to exhibition of those deficiencies that I now turn.

2. ZELLER AND ARMENDT ON THE SDAL

The notions of combat utility (CU) and degradation in combat utility (DCU) are central to the Zeller and Armendt view. On page 1 of their very long paper, they tell us that the meaning of combat utility will be discussed later. This is a promise they do not keep; the best they do is to tell us that the capability of a tank to perform close combat missions will be referred to as the combat utility of a tank. This is surprising in a work that purports clarity about underlying philosophy. We get a clue as to what they mean in their instructions to the SDAL panel concerning how the estimates of residual combat utility (RCU) should be made.

> As we go through the SDAL and you are trying to arrive at a value of RCU, try to envision all possible combat missions and how many of them would have to be aborted or done less well because of the loss of the specified component on the list (p. B9).

It appears that in DCU, Zeller and Armendt are seeking a measure of fractional capability—what percent of all combat missions could I not do, or would be done less well, given a certain damage state?

I do not know exactly what it means to say that a tank has a firepower DCU of 4. This is not meant as an uninteresting expression of ignorance on my part; I do not think that anybody else knows what it means either. Consider the following interpretations:

loss of 4 of rate of fire,
loss of .4 of acquisitions of enemy,
loss of .4 of hits on enemy,
loss of 4 kills vs. enemy,
loss of .4 of ammunition,
Boolean combinations of the above.

Which 40% have I lost? Is it the most important 40%? The least important? Since the notion of DCU is essentially content free, it is surprising that it has so long been accepted as a fundamental

metric in vulnerability analysis. This problem is entirely avoided if we construe vulnerability analysis such that our .4 result is a probability of kill (PK). For a carefully formulated damage criterion, it can be made crystal clear what it means when we say that the firepower PK = .4; this has been demonstrated in detail by Rapp (1983).

In the previous paragraph, I used the phrase "damage criterion;" it (and "kill criterion," which I use equivalently) is a traditionally used expression in vulnerability analysis. On page 5, Zeller and Armendt say (and I agree) that a kill criterion is a standard to which the effects of a given amount of damage can be computed in order to make a correct judgement as to whether or not a kill occurred. But then they immediately begin to distance themselves from the traditional idea that a damage or kill criterion is a go/no go threshold.

> There are two key assumptions underlying the vulnerability analysts' concept of PKH and its use. The first assumption is that a given amount of damage can only have one of two outcomes. The outcome can be either "kill," in which case the tank is useless and has DCU equal to 1.0, or "no kill," in which case the tank is considered to have full capability, which means DCU is equal to 0. In other words, the PKH model does not allow for the occurrence of intermediate levels of DCU. The second assumption is that the PKH applies to all combat missions that can occur during a war, which is the same as assuming that all missions have the same kill criterion.

Zeller and Armendt are cagey here. At first, one might be inclined to think that they are among the vulnerability analysts who make the two assumptions mentioned. However, they caution us that the two assumptions may be invalid, and the sequel makes clear that they reject at least assumption one. They reject assumption one in the next paragraph.

> In general, kill criteria can vary with the nature of the mission so that, potentially, each mission could have a unique kill criterion. Also, in general, there are levels of [damage] below the kill criterion for a given mission but with reduced effectiveness; that is, with a value of DCU that is less than 1.0 and greater than 0.

Here, Zeller and Armendt have contradicted themselves. Recall that by their own lights, a damage criterion is a "standard." The damage is enough to obtain a kill, or it is not. If the standard level of damage is achieved or exceeded, then that just means that the tank cannot continue merrily on its way. If the required damage threshold is not achieved, then the DCU for that kill criterion should be 0.0. Zeller and Armendt are motivated, I realize, by concern about damage states which are significant but below threshold, and I will address that legitimate concern below. However, the concern cannot

justify simultaneously regarding a kill criterion as a threshold and as an ill-defined region. Nor is this contradiction a slip of the word processor; Zeller and Armendt provide a graph embodying it.

We need to consider the assumption more closely. It certainly seems right and is consistent with the meaning of damage criterion that for a given level of damage, each criterion will be satisfied or not. However, it simply does not follow from this that there is no room for the occurrence of intermediate levels of DCU. We can define as many damage criteria as are required to clarify these intermediate levels. If need be, we can define 50 levels of mobility PKs. If somebody responds that there is a tactically significant level of intermediate damage between damage criteria 37 and 38, we can define a new criterion to capture the tactical significance of that intermediate level. So the first assumption is uncontentiously true; it keeps us from lapsing into self-contradiction and does not have the dire consequences associated with it by Zeller and Armendt.

We have seen that the problem of partial degradation or intermediate damage levels does necessarily not drive us to accepting a self-contradictory use of kill criterion. How did Zeller and Armendt get themselves into this box? I think it is because their posing of the problem is much too abstract. The vulnerability analyst must, in accordance with the second assumption, "seek the single value of PKH that best represents vulnerability integrated over all possible missions and over all levels of DCU." This is a Hegelian feat that I cannot accomplish, and it is apparent that Zeller and Armendt cannot either. Suppose we have convinced ourselves that we have accomplished the suggested mental gymnastics by performing the "integrations" and have obtained an average DCU value. It is completely unsurprising that such a globally averaged quantity will not correctly account for many cases of observed tank behavior. This is true by virtue of the meaning of "average." Hence, the immediate worry about intermediate damage levels. Zeller and Armendt regard this as a reductio ad absurdum of the idea that a damage criterion is a go/no go threshold. It would be more accurate, I believe, to regard it as a reductio of the possibility of meaningfully integrating over all possible missions.

Zeller and Armendt proceed to identify DCU and PK.

> Because of the way tank vulnerability assessments are used, it is necessary to measure the effect of tank damage in terms of the probability of "killing" an engaged tank. . . (p. 5).

Typical item and force-level models sample against a single shot probability kill (SSPK) value; the result of such sampling is usually either that the tank is removed from the game or that the tank retains its full capability. It is thought unlikely that such models will evolve to the point of handling more robust accounts of the matter in the near future. Thus, it is incumbent on the vulnerability community to supply PKs, and Zeller and Armendt recognize this. So what do they do? They simply identify DCU and PK in the following:

> . . . the assumption that averaged DCU is approximately equal to PKH averaged over all missions (p. 11).

Now this is clearly an attractive assumption because it immediately yields the required (BRL) output—PK. It avoids the intolerable vagueness of DCU; also, it makes available the powerful mathematical instrument of probability. So it really is a convenient assumption.

Unfortunately, the assumption is false. Even with its intolerable valueness, fractional combat utility is not the same thing as probability of total loss of capability. Ten tanks which have lost half their firepower (however defined) are not tactically the same thing as five tanks with all their firepower. I leave it to the tactically minded reader to invent scenarios in which ten is better than five, five is better than ten, and five is the same as ten. From the fact that there are scenarios which satisfy the third schema, it does not follow, of course, that the assumption is true in general.

There are also excellent mathematical reasons why it is not appropriate to identify DCU with PK. Under customary independence assumptions, it is legitimate to use the survivor rule for combining probabilities. There is no mathematical justification for combining DCU values in this way; such values are not even constrained to the 0-1 range, except by convention. Those who are not convinced that expected utilities are not probabilities are referred to the thorough and explicit discussion of Rapp (pp. 17–44).

The erroneous identification of fractional capability with probability of incapacitation has been with us for more than two decades. It is considered by Zeller (1965) on grounds of expediency, and is adopted without comment by Armendt (1974). Traces of the error can be found in many other places as well. It needs no emphasis that these historical matters do not allow us to avoid the conclusion that since the identification is erroneous, we must give it up. Utility values, when properly defined, give

us a measure of goodness; probabilities measure frequency of occurrence. It is a vain hope that we can cogently equate the two.

I believe that the arguments I have presented are sound; however, I also believe that SDAL proponents will not yet be convinced. Let us try to probe further into their motivation. Anticipating skepticism, Zeller and Armendt

> . . . ask why this [the SDAL process] method is used, couldn't the analyst define the spectrum of missions and then determine the weapon system performance required to implement them? The answer is that the spectrum and the variety of tank combat missions defy analytical description, as do the intangibles . . .that must be considered when estimating DCU (p. 12).

I want to speak to the "defy analytical description" claim and also to the insistence on "intangibles."

It is certainly true that the population of possible tank missions has infinite cardinality, cannot be explicitly enumerated in a finite time, and theoretically defies analytical description in that sense. However, the situation is not desperate. Although the set of possible missions may defy analytical description, the set of tank damage states need not.

Suppose there are N components in a target where the size of N is typically governed by how much we care about the target and how much information is available about it. If we assume that each component is killed or not, there are 2**N distinct combinations of components we might be interested in. If we could limit our attention to the C critical components needed for certain central classes of combat missions, we would be down to 2**C states. From a theoretical point of view, a vulnerability analyst (perhaps with the assistance of users, repairers, etc.) could associate loss of specific combat capabilities with each of the 2**N or 2**C damage states.

In either case, the set of damage states is finite, enumerable in theory, and does not "defy analytical description." Moreover, there is no reason, at least in theory, why each one of these states cannot be associated with a specific list of functions that could and could not be performed (or performed well). If we had the list of damage states and the functional mapping, we would have the tools available to answer any vulnerability question that might arise; this shows not only that the problem does not "defy analytical description" but also that SDALs are theoretically eliminable for the vulnerability analyses process.

An SDAL proponent might grant me this, but insist that the proposal is practically useless. My response to this is twofold. First, clarity requires that we distinguish the theoretically impossible from the practically difficult. More analysts and computer power can help with the latter but not the former. Second, significant work has already been done in reducing the 2**C states to a more tractable set for computation.

Let us turn to the second reason for embracing the concept of DCU—the "intangibles" that "defy analytical description." Zeller and Armendt's most explicit statement about these intangibles seems to be the following:

> CU involves more than the physical performance capabilities of the tank, such as its speed or rate of fire. The tank must perform as part of a unit. Thus, CU also involves less tangible factors such as the coordination of fire and maneuver with other elements of the unit the ability to cope with terrain obstacles (rocks, craters, and mines) and the ability to detect and react to enemy activity. Both battlefield surveillance and communications capabilities are important factors in effectively using the firepower and mobility of the vehicle in the context of a unit operation. All of these considerations must be factored into the measurement of combat utility (p. 2).

I do not dispute the importance of the factors Zeller and Armendt consider here; however, I do not understand the alleged intangibility. It cannot be disputed that it is difficult to associate 2**N distinct damage states with the types of capability cited in the quoted passage. But the fact that implementation of a probabilistic account of these factors is difficult does not imply that they are somehow intangible. Consider the following question: What intangibles cannot be accounted for by reference to one or more of the 2**N states? There are no such intangibles. Distinctions which are too subtle to be captured by differences in the 2**N states belong in metaphysics or theology, not vulnerability analysis. I conclude that there is no comfort for defenders of the SDAL process in the notion of intangibles.

We have seen that the lack of explicitness in the SDAL process is a serious problem; this problem arises partly but not exclusively because there is an undefined concept of utility at the center of the analytical structure. There are additional difficulties in the SDAL framework as well. One of these concerns lack of flexibility to address the diverse requirements of VLD customers. If a vulnerability question cannot be answered by traditional M, F, M/F, or K damage criteria, then the typical approach

has been to ask the customer to reformulate the question. If we concerned ourselves with a richer variety of damage states, we would be able to answer a larger variety of vulnerability questions.

Another class of difficulties with the SDAL process concerns the need for considering all possible combat missions. Some of the problems associated with this concept have been discussed previously. Here I want to focus on questions of tactical significance. I do not think that a few small groups of armor experts and vulnerability analysts should be given the implicit responsibility for making assumptions about the population of possible tank missions or about the relative importance of specific types of missions drawn from that population. Consideration of employment doctrine for tanks and of the expected frequency and relative importance of different types of engagements is not in the province of vulnerability analysts; it is the responsibility of the Army's Training and Doctrine Command (TRADOC). What the vulnerability community should be striving for is a more illuminating way of helping TRADOC exercise its doctrinal responsibilities.

A final argument in favor of abandoning the SDAL process is this—it would help the vulnerability analysis community achieve consistent configuration control. As matters currently stand, vulnerability analyses for some targets use DALs (Tanks, APCs), while analyses for other targets do not (helicopters, SAMs, SSMs, C3I systems). Dropping the SDAL out of the tank vulnerability analysis process would be a step towards equivalence of treatment in the vulnerability analysis of all target types.

We have seen that there are numerous problems with understanding the vulnerability analysis process along lines suggested by Zeller and Armendt. These problems include an unacceptably vague concept of utility, an unacceptably vacuous notion of "kill criterion," an illegitimate identification of utility with probability, and a requirement to integrate over all possible missions. It is time to take steps.

3. AN ILLUSTRATION

Let us consider a simplified example in enough detail to make the points more concrete. Suppose we are developing a Reliable and Mobile Protected Artillery System (RAMPARTS). Suppose further that RAMPARTS has three critical components—a man in a Kevlar vest, a step ladder, and a gun. Finally, let us simplify the problem still further and assume that we are considering large caliber

munitions such that a hit on a critical component is a kill. So there are 2**3 = 8 discrete damage states as shown.

RAMPARTS Damage States

State No.	Ladder	Gun	Man	Firepower Kill
1	1	1	1	No
2	1	0	1	Yes
3	1	0	0	Yes
4	0	1	1	?
5	0	0	1	Yes
6	1	1	0	Yes
7	0	1	0	Yes
8	0	0	0	Yes
1 – Survives 0 – Killed				

The combat utility of RAMPARTS derives its capability for shooting the enemy from long range. If either the man or the gun is killed, it cannot do that. There are six such damage states which, if realized, would result in a total firepower kill. The troublesome damage state is where the ladder is killed, but the man and the gun are not. RAMPARTS can no longer shoot at full range, but it can still shoot at a range somebody might describe as long. Should realization of this damage state result in a firepower kill?

Under the probabilistic account of the matter being developed here, the reasoning would be that we need two different damage criteria for firepower kills—one for long-range firepower kills (7 damage states) and one for total firepower kills (6 damage states). Note that the two different kinds of kill, the damage criteria, are explicitly defined as Boolean combinations of dead components. Then we can choose kill probabilities appropriate to the particular tactical situation we are trying to analyze. Notice that we have explicitly accounted for the "degraded" case where the ladder is lost.

Our SDAL proponent might reason differently. He might suggest convening a group of experienced RAMPARTS users and asking them that if the ladder is killed, but the man and gun are not, what is the combat utility or expected tactical loss of combat function of RAMPARTS? One member of the group relays a combat anecdote in which the visibility was so bad that use of RAMPARTS at long range was impossible; he concludes that loss of the ladder results in no loss of combat utility. Another member counters with an anecdote in which the long-range capability was crucial to mission success, so he believes that loss of the ladder implies complete loss of combat utility. Argument ensues. Other types of actual or potential missions are discussed. Finally, it is concluded that 50% of the possible firepower missions require the ladder. An entry would be made in the DAL that loss of the ladder results in a DCU of .5.

It requires emphasis that the group discussions needlessly obfuscate the question of appropriately weighing the criticality of the ladder. The probabilist provides firepower PKs both with and without the ladder and leaves it to the users of the vulnerability analysis to determine whether a particular problem requires total firepower PKs, long-range PKs, or some weighing of the two. Such users will argue for their choice of damage criteria and weighing; these arguments will be intrinsically public and susceptible to criticism and improvement. This is not true of the reasoning within the panels. A main advantage of the probabilistic approach in addition to fundamental mathematical coherence is that it can be fully explicit. It forces us to consider in terms of actual damage states the specific capabilities which contribute to the combat utility of a weapon. Is long range a key part of firepower? This question is perhaps considered in the consensus building process, but the answer is not explicitly available.

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APPENDIX:

1991 UPDATE

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The original paper was written in late 1987 and was published in American Defense Preparedness Association (ADPA) Proceedings in 1988 (Starks 1988). Substantial follow-on work has been accomplished at the U.S. Army Ballistic Research Laboratory (BRL), Aberdeen Proving Ground, MD, along the lines suggested in the paper. This has caused a fairly steady demand for reprints, which perhaps justifies the present publication in a more widely accessible form.

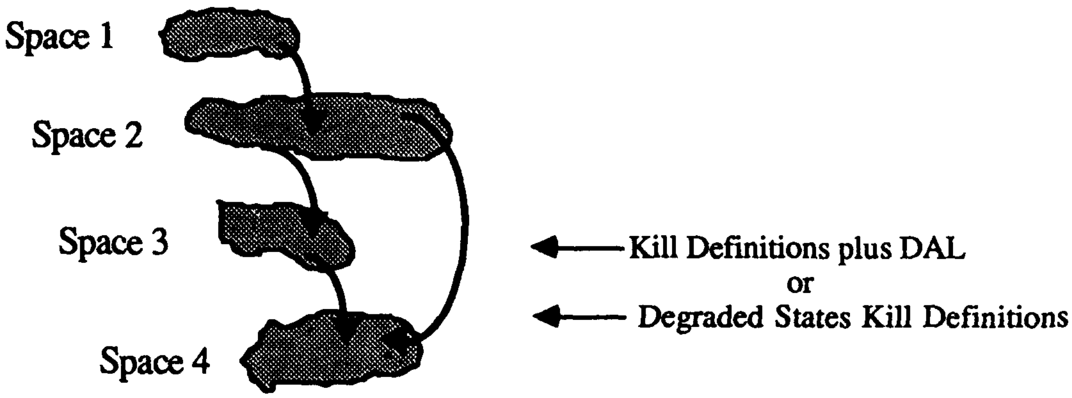
I have resisted the temptation to edit the paper into conformity with my current views; it is essentially identical to the ADPA paper. Thus, my first goal in this brief appendix is to describe what I now regard as the central infelicities of the original. I will also sketch some of the follow-on work which has been done and provide references for some of the relevant publications.

I believe that the criticism of Zeller and Armendt is sound and succeeds in articulating the most important problems inherent in the Standard Damage Assessment List (SDAL) framework. There is now widespread agreement among investigators in the field that the SDAL framework is fatally flawed.

Where the paper is weaker, I now believe, is in the overly simple view of the Vulnerability/ Lethality (V/L) problem which the Reliable and Mobile Protected Artillery System (RAMPARTS) example suggests. This can best be explained with reference to Figure A-1.

This four-space schema has been employed by a number of V/L investigators over the past few years to enhance the clarity of ongoing discussions on V/L matters. In the current terminology of the figure, the SDAL is a mapping from Space 2 damage states to Space 4 measures of effectiveness (MOEs) (Deitz et al. 1990). In hindsight, I now see that I was confused by the RAMPARTs analogy into equivocation on whether the Degraded States output metrics were in Space 3 or Space 4. For the RAMPARTs case, the eight possible damage states each map neatly into a specific Space 3 measure of performance (MOP). This led me to mistakenly conclude that we could also define specific Space 3 MOPs for targets such as tanks as a function of Space 2 damage vectors. I now believe that the conclusion was practically unwarranted.

If there are n components, each of which can be killed or not in a given Space 1 encounter, there are 2^n possible damage vectors in Space 2. For realistic targets, we must countenance n values on the order of thousands. And while it is *theoretically* possible to map each of 2^{1000} Space 2 damage



1. Warhead/Target Interaction
2. Component Damage State(s)
3. Measures of Performance (MOP's)
{ Loss of Automotive/Firepower Capabilities }
4. Measures of Effectiveness (MOE's)
{ Reduction in Battlefield Utility, "PKs" or "Losses-of-Function }

Figure 1. Conceptual Spaces of Vulnerability Modeling Applied to Armored Vehicles.

vectors into a specific Space 3 measure of target performance, it is not *practically* possible. What is possible is to group the Space 2 damage vectors in terms of which tree structures of components are cut to obtain a tree structure driven Space 4 MOE. This is essentially what has been done in the Degraded States (DS) Program, which I will describe briefly.

The important difference between specifically stating a Space 3 MOP for each Space 2 damage vector and binning the Space 2 damage vectors according to which Space 4 critical tree structures are cut is that the specific choice of tree structures to consider is, in a sense, arbitrary or at least partly *subjective*. I did not see this clearly when I wrote the original paper.

Although it is intellectually important to acknowledge that replacing the SDAL Space 2 to Space 4 mapping with a DS mapping does not purge the vulnerability analysis process of all judgmental elements, it is equally important to acknowledge that BRL's transition to the DS methodology has been clear progress towards the goal of increased objectivity.

As has been demonstrated by the Phase I (Starks, Abell, and Roach 1989) and Phase II (Abell, Rickter, and Burdeshaw 1990) DS programs, much greater clarity, auditability, and robustness have resulted from these programs. Our understanding of the analysis process has been considerably sharpened, and our understanding of the vulnerabilities of the analyzed vehicle has been substantially deepened. Over the next several years, BRL will approach full implementation of the improved methodology by conducting DS analyses of a wider variety of combat materiel.

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